A Faraday Cup for the Argonne Wakefield Accelerator and Photocathode Literature Survey

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<u>Abstract</u>

A Faraday cup has been built to measure the charge of electron bunches coming off the Argonne Wakefield Accelerator (AWA) beamline. Tests were done to determine if the cup is capable of resolving individual bunches separated by the AWA's RF period of 770ps. Results indicate that the cup has time resolution significantly below the required 770ps, allowing for precise measurement of bunch position in time relative to other bunches and to the target RF phase. A literature survey of photocathode technology and research was performed with the purpose of gathering and summarizing results and developments from multiple laboratories in a convenient format.

Introduction

This is a report on my work at Argonne National Laboratory as a participant in the Lee Teng Undergraduate Internship from June 7th – August 13th. During the internship, I worked in the Argonne Wakefield Accelerator (AWA) group in Argonne's High Energy Physics division. I learned about the basic principles of ultra-high vacuum (UHV) hygiene from my mentor, Dr. Zikri Yusof, and applied these principles while assisting him in the AWA Cs_2Te photocathode fabrication lab, preparing the vacuum chamber and deposition equipment for cathode production. I also performed analysis of data obtained from testing of a Faraday cup for the AWA beamline, and completed a literature survey of properties of various photocathodes used in electron beam generation.

Faraday Cup for the AWA beamline

A Faraday cup has been built with the purpose of providing precise measurement of the charge and timing of electron bunches coming off the AWA beamline. The Faraday cup was designed and built by former Lee Teng intern Teng Jian Khoo during the internship's inaugural year in the summer of 2008.[1] The primary focus of the cup's use in the AWA is to resolve the timing of consecutive bunches, with precise bunch charge measurement being a secondary goal. The AWA RF gun operates at an RF frequency of 1.3 GHz, which corresponds to an RF period of 770ps. Therefore the Faraday cup needs to have a time resolution of less than 770ps in order to resolve the arrival of consecutive bunches in a bunch train. The integrating current transformers which are currently used to measure bunch charge are incapable of precisely resolving individual bunches, thus creating the need for such a Faraday cup to be built.[2]

Previous studies of the cup immediately following its construction were done using only a single electron bunch. These tests indicated that the cup has a rise time of 50ps and that the full width at half maximum (FWHM) of the cup's signal is about 80ps (see Fig. 1). This is larger than the typical bunch length of ~10ps, but is still far shorter than the RF period of 770ps, indicating that the cup should be able to resolve consecutive electron bunches in experiments using extended bunch trains.[1]
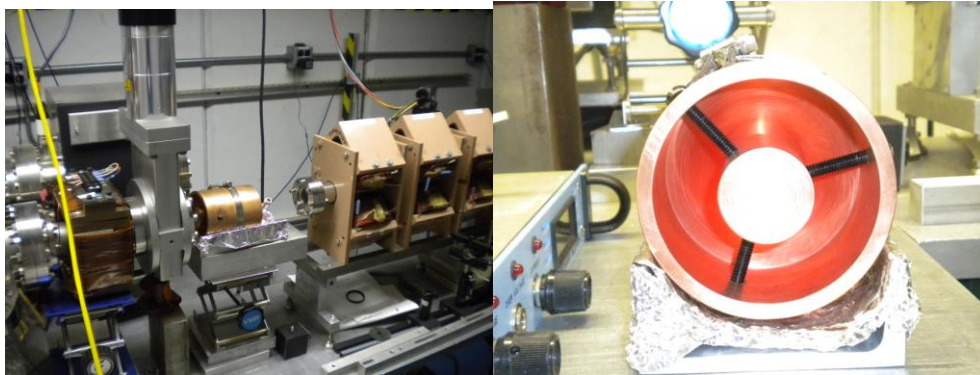
Left: The Faraday cup in place at the end of the AWA beamline.
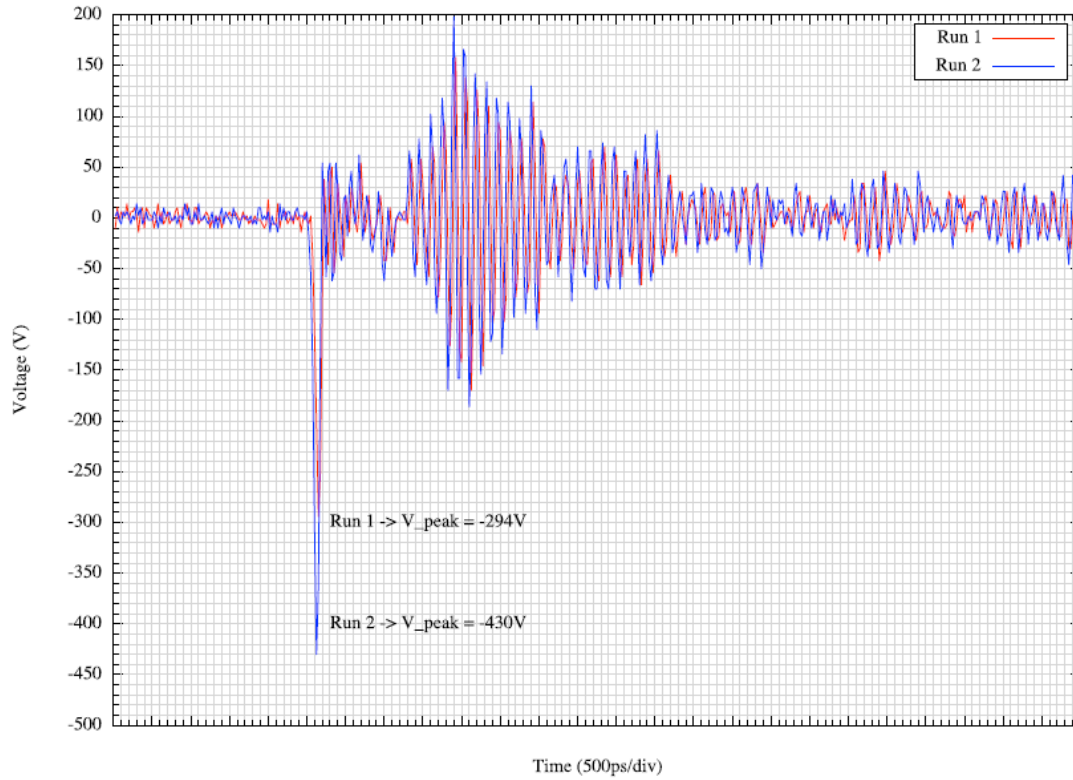Right: View of the cup's interior, showing the inner and outer conductors.

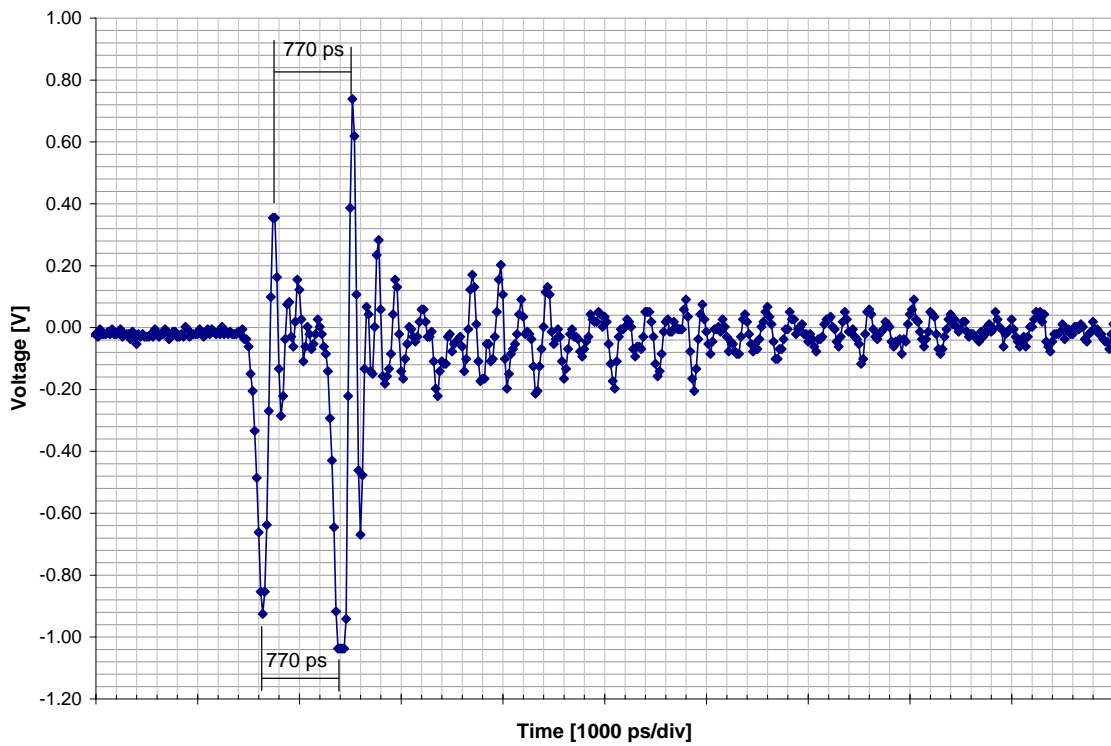Figure 1 – Faraday cup signal for single bunch test [1]

Figure 2 – Faraday cup signal for two bunch test

Further tests of the Faraday cup were planned for this summer to experimentally verify the cup's expected ability to clearly resolve consecutive bunches. However, due to extended downtime of the AWA drive laser for maintenance, a full test was unable to be performed. Therefore the only data available for analysis was that of a recent experiment using two consecutive electron bunches, during which the Faraday cup was in the beamline. Figure 2 shows the measured data from the cup for this experiment.

The graphed data shows two distinct peaks both in the positive and negative potential areas. Both sets of peaks, as indicated on the graph, are spaced 770ps apart, demonstrating that the Faraday cup can clearly resolve two consecutive bunches. The fast return to low potential directly after each peak indicates that the cup should be able to resolve many more consecutive bunches without significant distortion. The rise time observed from the data points is ~160ps for the first peak and ~180ps for the second peak. Given the nominal sampling rate of 20ps, the actual rise time is likely somewhere in between these two values. Still, it is evident that the observed rise time has increased about threefold from the rise time measured in 2008 after its construction.

The presence of the dual positive and negative peaks together, along with the noisy signal trailing the second bunch, can be attributed to two issues. The first tests of the cup indicated that the cup was ringing after each bunch was received, so it is logical to assume it is still doing so.[1] Also, the dual peaks are likely due to the lack of proper magnet alignment in the beamline for optimized beam, which was not necessary for the experiment being performed at the time. Therefore, the beam was likely spraying all over the cup, hitting both the inner and outer conductors, causing both the noise and the dual peaks. This also provides a likely explanation for the rise time increase, as two charges hitting the inner and outer conductors at almost the same time would have no net effect on the measured voltage signal, slowing down the rise time. Ideally, the signal would show only a negative peak as in Fig. 1 with no distortion on the trailing end. However, the cup's resolution is clearly sufficient to resolve separate bunches even with the significant noise included, so it can be expected that with proper beam optimization any ringing effect will not affect bunch resolution. Even so, it would be prudent to perform a full test of the cup with many consecutive bunches and optimized beam in order to verify these expectations, once the drive laser is in working order again. Also, this test should eliminate as many causes of distortion as possible to obtain an accurate prediction of the cup's performance in full accelerator operating conditions.

Photocathode Literature Survey

The science of photocathode fabrication is of key importance to the electron acceleration community, as well as to other applications of electron generation, such as electron beam lithography in the semiconductor circuit fabrication industry. These different applications generally result in different requirements for photocathode performance at each laboratory. Though over time fabrication procedures have become somewhat standard for certain widely used cathodes, much variation is still done in materials, procedure, and conditions in order to continually improve upon the available technology. In order to gather information about photocathode studies from many laboratories together in a condensed form, a literature survey was performed.

Many published papers were surveyed with a focus on the collection of several major pieces of information about the photocathode studies discussed in each paper. The specific cathode parameters of interest were: the material composition of the photocathode, the measured quantum efficiency (QE) values of the cathode, the wavelengths of light at which those values were measured (as QE varies with wavelength), the lifetime of the cathode both in storage and in active operation, and the method by which the cathode was fabricated. The data and a summary of any other experimental results found in the papers were recorded and compiled into a catalog, which can be found in the Appendix.

From the compiled information, several definite trends can be observed. Semiconductor photocathodes, such as the alkali antimonides and alkali tellurides, are the most popular cathodes in use in experiments with 'typical' cathode requirements – non-superconducting conditions, under ultra-high vacuum (UHV) of $10^{-9} – 10^{-10}$ Torr, and requiring sustained QE > 1%. Among these, cesium telluride (Cs_2Te) is the most commonly used material due to its high QE and relative stability in UHV conditions. Because of the common use of Cs_2Te, the method of fabrication of these cathodes has become somewhat standardized, with nearly all laboratories following the same process of sequential vapor deposition of a Te film onto a molybdenum substrate, followed by deposition of Cs until the measured photocurrent produced by the cathode reaches a maximum. This process is used in the AWA photocathode fabrication lab, and is detailed further in [1].

One of the major drawbacks to the use of alkali semiconductor cathodes is that their QE decays over time, and the speed of decay increases dramatically if poor vacuum is present due to the high reactivity of alkali metals with water vapor and oxygen. Therefore UHV conditions are required for the use of semiconductor cathodes, which can be difficult to attain or can become highly impractical in some applications. Fortunately, if such good conditions are not feasible, or if the cathode must remain in use for extended periods of time, alternatives do exist. Metal photocathodes were among the first to be used due to their robustness and ease of use. Their QE values are generally less than a tenth of a percent, several orders of magnitude below those of semiconductors, but metal cathodes do not show QE decay to the degree that semiconductors do and they can tolerate less stringent vacuum conditions. Additionally, they rarely require processing beyond initial

manufacture and thorough cleaning, whereas alkali tellurides and other types of cathodes require vapor deposition equipment and a UHV load-lock system to transfer the fabricated cathodes. This certainly makes metal photocathodes simpler to work with.

Several exciting new ideas in superconducting RF photoinjector design have been focused on the use of novel cathode materials. Significant research has been done into using the back wall of a niobium superconducting RF (SRF) cavity as the photoemissive material, which facilitates the development of SRF applications. This design allows for isolation of the cavity from other materials which could possibly contaminate the walls and ruin superconducting conditions. The QE results for this design fell short of expectations due to experimental issues, however. Other SRF cathode ideas have been explored, however, and good QE values above 0.5% have been obtained for lead films on niobium substrates. Certainly, the use of such cathodes for SRF photoinjector applications is quite promising.

A new and unique photocathode candidate has been found in Li_2CsSb, which according to studies done has broad sensitivity to light and a specific electron band structure which makes it easy to excite electrons but difficult to have them fall back down the band. These properties imply a possible QE near 100% for a broad spectrum of photon energies, which if realized alongside other favorable cathode properties could make Li_2CsSb the ideal photocathode.

Conclusions

Tests were performed on a Faraday cup to measure its ability to resolve the timing of electron bunches coming off the AWA beamline. Results showed that the cup has a resolution far below the required 770ps, which should allow it to precisely record the charge and timing of each bunch in full beam experiments. More in-depth testing is expected to be done to confirm these results. A literature survey was also done to gather information on photocathode research and results in order to facilitate reference to studies done at other laboratories.

Acknowledgements

References

[1]   Khoo, Teng Jian, "Photocathodes and a Faraday Cup for the AWA", available online at <http://www.illinoisacceleratorinstitute.org/2008%20Program/student_papers/khoo_teng_jian.pdf.pdf>

[2]   Discussions with Dr. Zikri Yusof, AWA group, High Energy Physics division, Argonne National Laboratory.

Appendix – Photocathode Literature Survey

All QE values given are initial values unless otherwise indicated. The lifetime values are specific to each laboratory and depend upon experimental conditions such as vacuum, laser power, details of fabrication, and threshold of QE below which cathodes are considered dead. In many cases for alkali cathodes, this threshold is 1%.
Below each paper's cathode data is a short summary of the paper's contents, and citations for each paper are listed at the end of the appendix.

Ref.	Photocathode Material	λ (nm)	QE	Storage Lifetime	Operational Lifetime	Fabrication Process
[1]	Ba	337	0.1%	n/a	Short-long	n/a
	Ca	248	0.05%	n/a	n/a	n/a
	Cs3Sb	266	2%	n/a	Very short	n/a
		527	4%	n/a	$T_{1/2} < 4$ h	n/a
			1-2%	n/a	n/a	n/a
		532	1.3%	n/a	n/a	n/a
			0.38%	n/a	1 to few hrs	n/a
		543	9%	n/a	n/a	n/a
	Cs3Sb + NaI/CsI/HTC	312	1%	n/a	n/a	n/a
	CsI	180	20%	n/a	n/a	n/a
		209	2%	n/a	$T_{1/2} > 150$h	n/a
		262	0.007%	n/a	n/a	n/a
	Cu	266	0.014%	n/a	Very long	Machined
	GaAs	527	5%	n/a	$T_{1/e} = 58$h	n/a
	GaAs + Cs	300	1.5-6%	n/a	short	n/a
	GaN/Cs	200	30%	n/a	n/a	n/a
	GaN/O/Cs	300	20%	n/a	10h	n/a
	KCsSb + CsBr	312	5%	n/a	n/a	Vapor deposition
	K2CsSb	527	8%	n/a	$T_{1/2} <4$h	n/a
		532	3%	n/a	$T_{1/e} >1$h	n/a
		534	4%	n/a	$T_{1/2} <2$h	n/a
		543	6%	n/a	n/a	n/a
	K3Sb	266	1.6%	n/a	Very short	n/a
		527	<1%	n/a	Short	n/a
		532	0.023%	n/a	1 to few hrs	n/a

Ref.	Photocathode Material	λ (nm)	QE	Storage Lifetime	Operational Lifetime	Fabrication Process
[1]	LaB6	355	0.1%	n/a	~1 day	n/a
	Mg	266	0.20%	n/a	Long	Laser-cleaned
			0.06%	n/a	>5000h	n/a
			0.027%	n/a	n/a	n/a
	Mg-Ba	266	0.1%	n/a	n/a	n/a
	Na2KSb	266	6.1%	n/a	Very short	n/a
		532	0.02%	n/a	1 to few hrs	n/a
	Nb	266	0.01%	n/a	n/a	n/a
	Rb2Te	266	4.5%	n/a	n/a	n/a
	RbCsTe	266	7.7%	n/a	n/a	n/a
	Sm	266	0.072%	n/a	n/a	Machined
	Y	266	0.05%	n/a	Long	Machined

This master's thesis provides significant, in-depth information about the fabrication process and phenomena of Cs2Te cathodes. Analysis of various parameters which influence QE values is provided, as well as X-ray photoelectron spectroscopy results which provide insight into the stoichiometries of Cs-Te compounds that form at given points in the deposition process, and how these compounds affect the QE for better or worse. Also, Mg cathodes are discussed in a similar way, as well as descriptions of the various diagnostic techniques utilized in the analysis of both cathode materials. Finally, a tabular overview of photocathode data and properties is given for many materials, the majority of which are reproduced above.

Ref.	Material	λ	QE	Storage Lifetime	Operational Lifetime	Fabrication Process
[2]	CdZnTe	222	0.0016%	n/a	n/a	n/a
		240	0.0024%			
		308	3.8×10^{-7}			
	CdZnTe (Cl doped)	222	0.033%	n/a	n/a	n/a
		240	0.0027%			
		308	3.8×10^{-8}			
	InP (Zn doped)	222	0.0017%	n/a	n/a	n/a
		308	5×10^{-7}			
	InSb (Cd doped)	222	0.025%	n/a	n/a	n/a
		240	0.00097%			
		308	2×10^{-7}			

Tests of the QE of various cathode materials were performed. Each material was tested under three light sources: a XeCl excimer laser (308nm), a Xe flash lamp (240nm), and a KrCl excimer laser (222nm). Data for InP under the flash lamp was not taken.

[3]	Cs2Te	251	16-18%	Several weeks	n/a	Vapor deposition

Rejuvenation to 10% is performed. Afterwards, cathode becomes more resilient to air exposure but does not maintain QE in storage. Rejuvenation thus restores QE, but leaves the cathode unstable, giving it a finite lifetime until it returns to low QE.

[4]	GaAs + Cs	633	~3.5%	n/a	several years	n/a

Tests of a negative electron affinity photocathode were done for use in a maskless lithography application. The fabrication and installation of the cathode are described. The original QE was quite low, on the order of 0.1%, due to overcesiation at the laser spot, but when the laser was shined elsewhere on the cathode the QE jumped to 3.5%. A cesium feedback loop was developed to control the current output of the cathode. A computer-controlled system turned cesium channels on or off based on the photocurrent being produced. The system was able to maintain a current between 1.64-1.68 uA for 8h before the cathode degraded sufficiently that additional cesium would not increase the photocurrent any further, at which point the loop failed. It was also observed that the cathodes used only degraded at 2.2mm diameter locations where laser light was shining. For a cathode of diameter 18mm, ~200 different emission sites can be used, extending operational lifetime to several years.

[5]	GaAs + Cs	635	1-8%	n/a	>80h	n/a

Presents studies of brightness and current density of negative electron affinity (NEA) cathodes. Larger extraction fields were shown to reduce the dispersion of charge density due to space charge effects by increasing the Langmuir-Child limit, which defines a maximum current density below which space charge effects will be negligible. Lifetime is also studied, and it was determined that recesiation of the cathode every 4h was sufficient to maintain QE at a relatively stable and usable level. Also, diagnostics of beam energy spread are described at various beam sizes, the results of which indicate that the method used provides a good measurement of the energy spread.

[6]	Cs2Te	262	1-3%	n/a	n/a	Vapor deposition

Discusses the calculation of thermal emittance for a photoinjector. Operational parameters for performing such a measurement are given, requiring a specific bunch charge of 3pC in order to keep space charge effects on emittance down and to ensure the signal-to-noise ratio is high. Finally, the scaling of thermal emittance with laser spot size and accelerating gradient are investigated.

[7]	GaAs	527	10%	>3 months	100h	n/a

Options for DC gun sources for an energy recovery linac (ERL) are discussed. The major candidates for the electron source are GaAs and alkali antimonide cathodes. GaAs is discussed at length due to being used in the JLab FEL DC gun. It is able to produce the ERL-targeted 100mA current for ~100h before the QE decays to 2.39%, which brings the current under the 10W laser below 100mA. Thus the lifetime for an ERL application is short due to the high current requirement. There is interest in alkali antimonides, which are positive electron affinity (PEA) cathodes whereas GaAs is a negative electron affinity (NEA) material. The PEA cathodes may have a longer lifetime in the ERL, which makes them considerably stronger candidates.

[8]	Cs2Te	266	2%	n/a	n/a	Vapor deposition (overcesiated)
	Nb	n/a	0.37%	n/a, assumed very long	n/a, assumed very long	Chemically etched, mechanically polished with diamond compounds, ultrasonically cleaned

Tests were done on an overcoated Cs2Te cathode to determine the effect of overcoating on cathode durability. A favorable result would indicate that such cathodes could be fabricated elsewhere and transported to RF guns for use. The cathode showed an order of magnitude decay in QE from 2% to 0.2% during transfer, and possibly can be rejuvenated back to 1-2%. A partial pressure of 10^{-4} Torr of water vapor was found to defeat the thicker layer of Cs, implying that better vacuum conditions during transfer would be necessary. Also discussed is the possible use of a niobium cathode in a superconducting niobium RF cavity. This would allow for electron production in SC conditions without the need to introduce foreign materials into the chamber. The Schottky effect is used to improve the practical QE of the cathode.

[9]	KCsSb	312	30%	n/a	n/a	Vapor deposition
	KCsSb + 20nm CsI	312	10%	n/a	n/a	Vapor deposition
	KCsSb + 25nm CsI	312	4-5%	n/a	n/a	Vapor deposition

Coatings of CsI and CsBr on the cathodes are used in order to provide protection from air poisoning. The results show a trade-off between QE and robustness - initial QE of 30% can be attained with an uncoated cathode, but it decays to less than 2% in 10^{-5} Torr of oxygen. A cathode coated with 25nm of CsI, on the other hand, has an initial QE of 4-5% but is stable for over an hour at >100 Torr of oxygen. Intermediate thicknesses produce expected results: QE decreases and robustness increases with increasing thickness. Unfortunately, these coatings do not provide any protection against H2O vapor above 10^{-5} Torr, which destroys the cathode.

| [10] | Cs2Te | 211 | 8.9% | n/a | n/a | Vapor deposition |
| | | 264 | 12.1% initial, 5.1% with O2 | n/a | n/a | Vapor deposition |

| The paper presents the first direct measurement of thermal emittance from Ag and Cs2Te cathodes. The second QE value for 264nm Cs2Te is the result of intentionally exposing the cathode to oxygen in a controlled way to replicate actual conditions in an RF gun, and thus get a more practical QE measurement. |

| [11] | Cs2Te | 254 | 10-13% | n/a | n/a | Vapor deposition |

Early studies of Cs2Te fabrication methods and results are presented. The effect of temperature during deposition of the Cs2Te cathode was studied at 120°C and 23°C. The "cold" method produced a higher initial QE than the "hot" method, but it quickly decayed down to the initial value obtained with the "hot" method. The "hot" procedure, on the other hand, stayed stable at its initial QE after fabrication, indicating that temperature does not have an effect on the stable QE of a cathode. X-ray photoelectron spectroscopy (XPS) studies were done on a cathode during fabrication with the "hot" recipe. XPS data was taken at several points during the fabrication and the analysis shows the presence, ratio, and stoichiometry of the various Cs-Te compounds in the film. Oxygen was also detected trapped beneath the Cs, indicating that an oxide layer was left behind during the cleaning process prior to deposition. Also, a cathode was exposed to increasing amounts of oxygen to determine QE loss due to oxygen poisoning. An important result is that Cs2Te requires 1000 L of oxygen exposure to reduce its QE by an order of magnitude, whereas it has been shown that K2CsSb requires only 1 L to experience the same factor of decay, demonstrating that Cs2Te is far more robust. Finally, the cathode was rejuvenated via a combination of heating and activation with 254nm UV light, with heating alone producing no results.

| [12] | Cs2Te | 263 | 8-12%, 3-5% stable | n/a | >100h at stable QE | Vapor deposition |

A Cs2Te cathode was tested in the Los Alamos free electron laser, and a comprehensive characterization of the electron beam is presented. Also described are the operating parameters and features of the RF photoinjector and linac. The performance of the Cs2Te cathode was determined to be superior to K2CsSb cathodes previously used, with low dark current and comparable emittance measurements.

[13]	Ca	248	0.004%	n/a	n/a	n/a
	Cu	248	0.004%	n/a	n/a	n/a
	Mg	248	0.013%	n/a	n/a	n/a
	Y	248	0.001%	n/a	n/a	n/a

Preliminary results of the Argonne Wakefield Accelerator (AWA) are presented, along with photocathode data for several materials tested in the photoinjector gun. Properties of the accelerator itself are given, including data on the emittance, position, and time structure of the beam. Mg was chosen as the best candidate for the gun, though the AWA group has since switched to Cs2Te cathodes.

[14]	Cs2Te	254	~8%	long	>2 months	Vapor deposition

Discusses the measurement of several properties of Cs2Te cathodes, including mapping the QE uniformity on the cathode at various wavelengths. 254nm was found to have the most optimal uniformity. The same testing was done on both fresh cathodes and cathodes that had been used in a RF gun or stored for long periods of time. One cathode was tested after long storage and was found to have a similar QE to a fresh one, though its work function values across the surface were up to 0.4 eV higher, a significant change that is highly relevant to thermal emittance. The authors caution that these results indicate the QE is not the only important parameter in the characterization of cathodes, especially when emittance is an important design factor.

[15]	Pb	193	.54%	n/a	n/a	Arc deposition onto Nb substrate

The possibility of using a lead cathode in a superconducting Nb cavity is discussed. Various methods of creating the lead cathode were tested, with the best results uniformly coming from arc deposited lead on Nb substrate. QE values given are for arc deposited lead on Nb - all other methods tested produced significantly lower QEs, and therefore arc deposition is recommended.

[16]	Al	213	0.084%	n/a	n/a	n/a
		266	0.0032%	n/a	n/a	n/a
		355	3.4×10^{-7}	n/a	n/a	n/a
	Au	213	0.04%	n/a	n/a	n/a
		266	0.0013%	n/a	n/a	n/a
	Cs3Sb	213	3.5%	n/a	n/a	n/a
		266	2.0%	n/a	n/a	n/a
		355	1.8%	n/a	n/a	n/a
		532	0.38%	n/a	1 to few hrs	n/a
	Cs2Te	266	3.3%	n/a	>1 week	Vapor deposition

[16]	CsI	193	9.6%	n/a	n/a	n/a
		213	6.8%	n/a	n/a	n/a
		266	0.0071%	n/a	n/a	n/a
		355	0.00019%	n/a	n/a	n/a
	CsI + Ge	213	0.73%	n/a	n/a	n/a
		266	0.13%	n/a	n/a	n/a
		355	0.0002%	n/a	n/a	n/a
	Cu	193	0.02%	n/a	n/a	n/a
		213	0.015%	n/a	n/a	n/a
		266	0.00022%	n/a	n/a	n/a
		308	1.6×10^{-7}	n/a	n/a	n/a
		355	8.0×10^{-7}	n/a	n/a	n/a
	K3Sb	213	1.4%	n/a	n/a	n/a
		266	1.6%	n/a	Very short	n/a
		355	0.76%	n/a	n/a	n/a
		532	0.023%	n/a	1 to few hrs	n/a
	Na2KSb	213	7.7%	n/a	n/a	n/a
		266	6.1%	n/a	Very short	n/a
		355	3.5%	n/a	n/a	n/a
		532	0.02%	n/a	1 to few hrs	n/a
	Sm	308	0.00016%	n/a	n/a	n/a
	Stainless steel	213	0.009%	n/a	n/a	n/a
		266	0.016%	n/a	n/a	n/a
	Y	266	0.00027%	n/a	n/a	n/a
		308	0.00011%	n/a	n/a	n/a

Many different types of cathodes, including metals, alkali halides, and alkali antimonides were tested thoroughly for determination of the best candidate for service in an RF gun. The metals were determined to have too low QE, and were eliminated. The halide CsI was favored for its good resilience to air exposure (as the facility did not have vacuum transport capability) but required laser wavelengths that were too impractical to use. Thus Cs2Te became the favored cathode.

[17]	Al/Sm(10% Sm)	193	0.029%	n/a	n/a	Vapor deposition at 125°C
	Al/Sm(50% Sm)	193	0.027%	n/a	n/a	Vapor deposition at 125°C
	Al	193	0.076%	n/a	n/a	Vapor deposition at 125°C
	Al	193	0.061%	n/a	n/a	Vapor deposition at 25°C
	Al	193	0.049%	n/a	n/a	Vapor deposition at 125°C, then glass bead blasted
	Diamond/Mo polycrystal (B doped)	193	0.028%	n/a	n/a	Vapor deposition at 125°C
	Diamond/p-type Si polycrystal (B doped)	193	0.325%	n/a	n/a	Vapor deposition at 125°C
	SiC (Al doped)	193	0.013%	n/a	n/a	n/a

Required operation at 1E-6 Torr precludes the use of multialkali cathodes, thus alternative cathodes are studied. Temperature at fabrication was varied for Al, using the typical 125°C and room-temperature 25°C, with the hotter temperature producing better QE. Bead blasting was tested as a cleaning and surface area increasing technique on Al, but the QE worsened as a result. Mo and Si were tested as substrates for diamond films, with the silicon substrate producing higher QE by an order of magnitude than any other tested material, indicating that such diamond on silicon cathodes could be a good, feasible choice for HV conditions.

| [18] | Cs2Te | 263 | ~13% | n/a | >100h | n/a |

Discusses many cathode materials, but shows that for the given operating circumstances, Cs2Te is the superior choice. Several lifetime analyses were done on Cs2Te cathodes by placing them under poor vacuum conditions for periods of time and tracking the QE decline, then attempting to rejuvenate them and observing the effects. It was determined that temperatures between 150°C and 200°C were best for rejuvenating air-contaminated Cs2Te cathodes.

[19]	Ag	266	0.002%	n/a	n/a	Machined
	Au	266	0.0047%	n/a	n/a	Machined
	Cu	266	0.014%	n/a	Very long	Machined
	Mg	266	0.062%	n/a	n/a	Machined
	Ni	266	0.0025%	n/a	n/a	Machined
	Pd	266	0.0012%	n/a	n/a	Machined
	Sm	266	0.072%	n/a	n/a	Machined
	Ta	266	0.001%	n/a	n/a	Machined
	Tb	266	0.0235%	n/a	n/a	Machined
	Y	266	0.05%	n/a	Long	Machined
	Zn	266	0.0014%	n/a	n/a	Machined
	Zr	266	0.001%	n/a	n/a	Machined

Many metal photocathode materials were tested for feasibility of use in a switched power linac. The experimental setup and procedures are well described. Scaling of electron yield with illuminated area and with increased laser energy was tested, as well as quantum efficiency values for low fields. Limitations on current density due to space charge and optical damage from the laser pulses are defined and explained. Finally, field-assisted emission using the Schottky effect is explored. The authors determined that for field gradients below ~100MV/m, Y or Sm would be good cathode choices, but if the field gradients rose above that level it would be better to use Cu due to the possibility of breakdown with those low work function materials.

[20]	CsI + Ge	262	~0.5%	n/a	>1 year	Vapor deposition
	Cs2Te	262	~10%	n/a	~20 days	Vapor deposition
	K2Te	262	1-3%	n/a	n/a	n/a

Several types of alkali photocathodes were tested in the drive beam RF gun of the CLIC photoinjector, and results are provided. A short description of several fabrication procedures is also included.

[21]	Cu + nano C	532	$\sim 10^{-9}$	n/a	n/a	Machined; C film added via beam deposition

Describes addition of nanostructured carbon films onto metal substrates to form a protective layer against gas poisoning. Films of 20nm thickness do not affect photoemission from metal substrates, and films thicker than 70nm completely determine the photoemissive properties of the cathode. It is possible that such thin films could maintain the QE of alkali photocathodes and reduce damage from residual gases, allowing for longer lifetimes and/or less stringent vacuum requirements.

Ref	Material	λ	QE			Method
[22]	Nb	248	0.003%	Very long	Very long	Small knob added to back of chamber wall during design and construction
		266	0.0002%			

The idea of a superconducting (SC) RF injector using the back wall of the Nb SC RF cavity as the electron source is discussed. The benefits of such a setup would be superconducting RF with no need to replace or manipulate a different material as a cathode inside the chamber. Room temperature measurements of the QE indicated QE values >0.01% after cleaning with an excimer laser, but such values were not obtained at SC temperatures. The authors theorize that the cathode acted as a cryopump, adsorbing the laser ablated material as it was removed, negating the cleaning process entirely. This is made more likely by the fact that the nearest vacuum pump was 1 m away.

Ref	Material	λ	QE			Method
[23]	Cs2Te	262	10%	$T_{1/2}$= 3 months	~105 days	Vapor deposition
	CsKTe	262	~20%	n/a	>100 days	n/a

A description of photocathode production and vacuum transfer procedures is given. The QE and lifetime of several cathodes is also described, and an in-depth analysis of dark current produced by many cathodes is presented as well. Results indicate that the dark current is significantly reduced by ensuring a mirror-like polish on the substrate surface. Also, a new RF gun's installation and the old gun's transfer to a different laboratory showed a high dark current in the new gun and the same low value in the old gun, which implies that a significant reduction in dark current is caused over time by a conditioning effect of the RF gun.

Ref	Material	λ	QE			Method
[24]	Cs2Te	254	~8.5%	n/a	100-200 days	Vapor deposition

The cathode preparation and transportation systems and processes used by FLASH are described. The process for measuring quantum efficiency is also described in detail. Degradation of QE is attributed to vacuum issues in the RF gun, and not to an extracted charge limitation on the cathode.

Ref	Material	λ	QE			Method
[25]	Cs2Te	262	~8.5%	long	>2 months	Vapor deposition

Describes the problems with QE stability that have been present in the FLASH photoinjector system and how they were fixed. Such problems include fluorine leaks from Teflon rings in the vacuum chamber, Mo, Fe, and Ag particles introduced from the transfer system, and excessive sparking and dark current from a bad RF contact spring. It should be noted that though FLASH uses a QE of 0.5% as their end of lifetime threshold, they sometimes change cathodes early due to low self-amplified stimulated emission (SASE) energy levels, so the operational lifetime of these cathodes may in fact be longer than reported.

[26]	B cathode[1]	266	0.035%	n/a	n/a	Commercially manufactured
		355	0.001%			
		532	0.0025%			
	M cathode[2]	266	0.26%	n/a	n/a	Commercially manufactured
		355	0.14%			
		532	0.03%			
	Scandate[3]	266	0.08%	n/a	n/a	Commercially manufactured
		355	0.02%			
		532	0.0065%			

Dispenser photocathodes are investigated as candidates for applications requiring robust, high duty factor photoemitters. Theoretical simulations were done and the results were compared to experimental data and available literature on the cathodes tested. The simulations were shown to compare well to real data, validating the simulation code's utility. From the simulations, the M cathode should attain a QE of 0.9% for UV light under high field and high laser intensity conditions, making it a solid photocathode candidate for applications requiring such conditions.

| [27] | Cs2Te | 262 | ~8%, ~5% stable | n/a | ~80 days | Vapor deposition |

Describes high-QE photocathodes which are produced for use in two European photoinjector facilities. QE decay in the gun is analyzed via the use of QE mapping at various points in a cathode's lifetime. It was shown that visible discoloration of the cathode film accurately corresponds to the pattern of QE decay on the cathode obtained by mapping. Also, the primary source of QE decay was attributed to the laser beam itself, as post-use cathode mapping shows a low QE region which is the same size as the laser spot. This also demonstrated that the cathode was not perfectly centered in the RF cavity, as the laser was aligned with the electrical center of the RF gun but the low QE area on the cathode was displaced to one side off of its center. It is suggested that mapping technology be explored further as a tool for online diagnostic purposes.

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[1] sintered tungsten matrix impregnated with barium calcium aluminate
[2] sintered tungsten matrix impregnated with barium calcium aluminate, with thin osmium coating
[3] sintered tungsten matrix impregnated with scandium oxide

[28]	CsK2Sb	541	~1.2%	n/a	n/a	Vapor deposition

In-depth characterization is given of chemical reactions which result in the production of alkali antimonide photocathodes. One deposition reaction described in this paper is exothermic, permitting single-alkali cathodes to be fabricated at room temperature. Cs3Sb cathodes have been produced at room temperature with comparable QE's to cathodes heated during fabrication. The conclusion is drawn that the evaporation procedure used to create a CsK2Sb cathode is not an important factor in determining QE, as the variation in results from using different recipes is less than the variation in results from using the same recipe multiple times.

[29]	Cs2Te	266	~10%	Long	~1.5 weeks	Vapor deposition
	CsK2Sb	532	>10%	>10,000h in UHV, 20h in HV	>10,000h in UHV, 20h in HV	Vapor deposition
	GaAs + Cs	532	2-6%	long	long	n/a

Various photocathode options are discussed in the context of energy recovery linacs. Cs2Te specifically is discussed in relation to its lifetime and QE performance. As expected, Cs2Te has high QE but a short lifetime. However, its lifetime can be increased via several methods. Overcesiating the surface has shown to increase lifetime significantly, and simultaneous deposition of Cs and Te has shown to increase both lifetime and QE. Also, evaporation of a layer of CsBr onto the cathode surface has shown to extend lifetime. A newly proposed technique involves the use of a thin diamond layer between the cathode and injector, preventing contamination, which also results in a significant (>100-fold) secondary electron gain. Rejuvenation of the Cs2Te cathode is not discussed, even though other papers have shown it to be a good technique for extending operational lifetime.

[30]	Cs2Te	262	4-6%	~1 month	~3 months	Sequential deposition or coevaporation

Includes a detailed discussion of possibilities for superconducting RF guns, including concerns over whether to use superconducting (SC) photocathodes or normal conducting (NC) cathodes, and the benefits and problems with each. The authors decided to use a NC Cs2Te cathode because of its high QE and rejuvenation capability, but were thus required to ensure thermal isolation of the cathode from the SC Nb wall, and prevent the cathode material from contaminating the SC wall itself. A UHV system was constructed with a transfer chamber, in which finished cathodes are stored. However, the vacuum in the chamber increases temporarily during transfer due to friction between the parts releasing adsorbed gas. This effect is believed to be the cause of a significant observed QE decay during transfer, though the QE of a cathode in storage and in the gun was shown to remain quite constant over time. The authors attribute the particularly high and resilient QE to coevaporation of the Cs and Te during fabrication. Up to two rejuvenations have been found possible with diminishing returns on the QE gain, and a third attempt did not produce any improvement of QE.

[31]	Cs2Te	254	>6%	n/a	n/a	Vapor deposition

Analysis of the process by which Cs + Te compounds form on the substrate, including the various stoichiometries which form during deposition. Also presented is an analysis of the oxidation of Cs, its drastic effect on QE, and a method by which to rejuvenate such oxidized cathodes using 230°C temperatures and UV light below a certain energy threshold simultaneously. The wavelength of the threshold is between 254nm and 300nm.

[32]	Cs2Te	262	~10%	n/a	>120 days	Vapor deposition

Describes vacuum conditions which preserve cathode QE over long time periods of storage. Though the cathodes have comparable QE to fresh ones after 120 days in the RF gun, they are often changed out at this point due to the ease of generating high self-amplified stimulated emission (SASE) energy levels with fresh cathodes. Studies are also done on the effect of varying accelerating field gradients on quantum efficiency in the gun.

[33]	CsK2Sb	527	5% - 12%	>10,000h	1-10h	Vapor deposition

Details processes of rejuvenation, particularly a "multi-layer" technique which fabricates a new cathode on the residue of a previous one after heating it to 150°C to remove residual cesium. Also discusses the improvement of initial QE below the expected value by exposing the cathode to water vapor in RF cavity vacuum. The lifetime of the cathode is discussed in terms of causes of decay. Water vapor accumulation and cesium evaporation are major causes, though the former is eliminated at temperatures of 120°C and the latter is a non-issue at ambient 25°C. The best lifetimes are found to be achieved at 120°C, where water evaporates as fast as it accumulates, though the lifetime is still limited by cesium evaporation.

[34]	CsK2Sb	355	10%	n/a	>2 months	Vapor deposition
		532	3%			

Discussion of QE results are presented for CsK2Sb cathodes with the focus of using them in a superconducting RF photoinjector. Higher QE was obtained at 355nm, however 542nm was chosen for use due to laser power limitations. Also discussed are beneficial effects on QE from exposure of substrates to small amounts of oxygen prior to deposition. For Mo and Cu plugs, the QE of the resulting cathode after oxygen exposure approximately doubled from values obtained without oxygen exposure. More testing on this phenomenon was planned. The final experimentation done was monitoring the QE while lowering the cathode temperature to 170°K. The QE remained constant until about 190°K, after which it slowly decayed with cooling. The explanation is that as cooling continues the cathode begins to cryopump the residual gas in the chamber, poisoning itself. Nevertheless, the QE at 170°K was only slightly below the room temperature value, indicating that this material is a good choice for superconducting RF applications.

[35]	Cs2Te	262	>7% at 6 months, >2% at 2 years	n/a	>2 years	Vapor deposition
	CsI + Ge	262	~0.5%	n/a	>1 year	Vapor deposition
Presents a summary of general properties of many types of photocathodes alongside various new ideas for improvement. These new ideas include the adding of protective films of nanostructured carbon onto alkali cathodes to protect the photoemissive surface from contamination and the testing of ferroelectric ceramics as a new type of photocathode.						

[36]	K2Te	259	8.3%	n/a	n/a	Vapor deposition
Presents results on the photoemissive properties of K2Te as a promising cathode candidate. Several fabrication processes are discussed, which vary in temperature and evaporation stopping point. The highest QE's are obtained by fabricating with the substrate at room temperature, and stopping when the measured photocurrent reaches a maximum. No long-term storage tests have yet been done, and the effect of in-gun conditions is unknown, so it is unclear how the lifetime of these highest QE cathodes compares.						

[37]	Cs2Te	263	>10%, ~2% stable	n/a	>4 years	Vapor deposition
Studies changes in QE and dark current in an RF gun, specifically a noticeable increase/decrease over time spent in the UV laser. Also, dark current sources were investigated and it was determined that both the cathode itself and the magnetic focusing elements were responsible for dark current. The magnetic elements produce dark current by guiding electrons differently depending on their energy, which varies due to emission at different RF phases (an effect commonly known as dispersion).						

[38]	PLZT[4]	532	0.0001%	Long	Long	n/a
Discusses the implementation and properties of ferroelectric ceramic photocathodes, which are robust and appear to be insensitive to vacuum conditions. Additionally, they require little processing, operate under green light, and have nonlinear efficiency with respect to laser intensity, which reportedly could allow for QE above the attained value. No lifetime data is given, but it can be presumed that the lifetimes both in and out of the gun are long due to the tough nature of the ceramic.						

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[4] ferroelectric lead zirconate titanate lanthanum doped ceramic

[39]	Cs2Te	262	~10%	n/a	39 days	Vapor deposition
X-ray photoelectron spectroscopy was performed on two newly fabricated Cs2Te cathodes to further understand the chemical composition of the film and to possibly gain a better understanding of the degradation of QE. The laser pulses of the XPS system revealed peaks corresponding to oxygen contamination, but as pulsing continued this evidence was diminished, indicating that the laser pulses were producing a net heating effect, which removed the contamination as in a typical rejuvenation process. XPS was also done on used cathodes, which indicated a shift from oxidized Te^{+4} and Te^{+6} states to the metallic Te^0 state, indicating that the QE degradation of these cathodes was in fact due to loss of cesium causing Cs2Te to shift to pure Te. The oxygen lines also disappeared, indicating that the RF gun drive laser pulses create a similar heating effect to rejuvenate the cathode in the gun.						

[40]	Cs2Te	262	~10%	n/a	~90 days	Vapor deposition
Discusses various properties of Cs2Te photocathodes. The process of coating growth on the cathode is described, as well as a characterization of the resulting QE distribution using mapping. The uniformity is very good, with high QE in the center and progressively decreasing QE radially outward. Trends of dark current measurements in the RF gun are also presented. The lifetime of these cathodes was determined to be mainly limited by QE decay and dark current development in the cavities.						

[41]	GaAs + CsO	632	~4%	n/a	2-4 days	Vapor deposition
A negative electron affinity (NEA) cathode is characterized in an electron gun. CsO is evaporated onto the GaAs cathode surface to establish NEA conditions. Particular graphical detail is given to analysis of QE changes during operation on both normally coated cathodes and overcesiated cathodes. Normal cathodes always experience QE decay in time due to electron stimulated desorption and laser damage to the cathode surface. However, overcesiated cathodes start out with a lower QE and as electrons are produced, they cause Cs to diffuse from the emission point, reducing the layer thickness atop the CsO layer and increasing the QE. Once the excess Cs has been completely removed, the CsO is exposed and QE reaches a maximum. However, eventually the CsO layer is damaged and the QE decreases at that point. Electrons then move around the damaged spot and the Cs surrounding it begins to degrade, increasing QE at those points. Lifetime results for these cathodes are unimpressive, but techniques to improve lifetime have been theorized and could result in an order of magnitude increase.						

[42]	CsKTe	259	~22.5%	>100h	n/a	Vapor deposition
A detailed discussion of the fabrication process and results for CsKTe cathodes is given. The best QE values have been obtained by depositing Te, then K, and finally Cs. Alternating the K and Cs steps in fabrication has been considered, but switching the two decreases the resulting QE. This cathode material is determined to be a very good candidate, possibly better than Cs2Te, although the authors caution that obtained QE values appear to be extremely dependent on fabrication conditions. The lifetime of these cathodes in operation appears to be directly analogous to their lifetime in UHV storage.						

[43]	Cs2Te	251	~15%, 3-5% stable	n/a	>100h	Vapor deposition

A detailed discussion of Cs2Te fabrication procedures is given. Also, several cathodes were QE mapped to determine their uniformity, which was generally good except for a definite bias towards one side of the surface. This was determined to be due to the angle and facing location on the cathode of the Cs and Te dispensers. This non-uniformity can be removed by repositioning the dispensers to aim farther toward the respective near sides of the cathode instead of at the center, but due to the extensive calibration required this has not yet been done.

[44]	GaN	312.6	0.0001%	n/a	n/a	Beam epitaxy
	GaN/Cs	312.6	50%	n/a	n/a	Beam epitaxy + Cs activation
	GaN/O/Cs	312.6	48%	n/a	n/a	Beam epitaxy + O/Cs activation
	GaN/Cs/O/Cs	312.6	40%	n/a	n/a	Beam epitaxy + Cs/O/Cs activation
	GaN/Ba	312.6	3%	n/a	n/a	Beam epitaxy + Ba activation

GaN films are tested as electron sources, including tests of several different activation methods to improve their performance. Activations done were Cs, O/Cs, Cs/O/Cs, and Ba. The first two reduced the work function of the cathode by 2.4eV, the third by 2.0 eV. It is clear that these reductions in work function are highly beneficial, as QE increased by five orders of magnitude. The Ba activation was shown to produce QE an order of magnitude below the others, which is still a very large improvement over the non-activated cathode. The Ba activation had not yet been sufficiently studied to determine its work function effect or other properties.

[45]	InGaN (p-type Mg doped)	325	19%	>1 week	>60 hrs/spot	Crystal grown on sapphire substrate

A negative electron affinity cathode was tested as a practical electron source. A detailed description of the experiment is given. Data and analysis is presented on the spectral sensitivity, lifetime, energy spread, and robustness of the cathode. The cathode was found to be quite robust, showing almost no decay in 10^{-7} Torr oxygen. This cathode material was determined to be an excellent candidate due to its high QE values and robustness.

[46]	Li2CsSb	all colors	~100%	n/a	n/a	n/a

Li2CsSb has a unique direct band gap in the red portion of the spectrum, thus making it sensitive to all colors. Its crystal and band structure also apparently make it very difficult for excited electrons to drop back down into the valence band, making a QE near 100% possible.

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